Features of energetic particle transport in the after-glow phase of the JET plasma discharges

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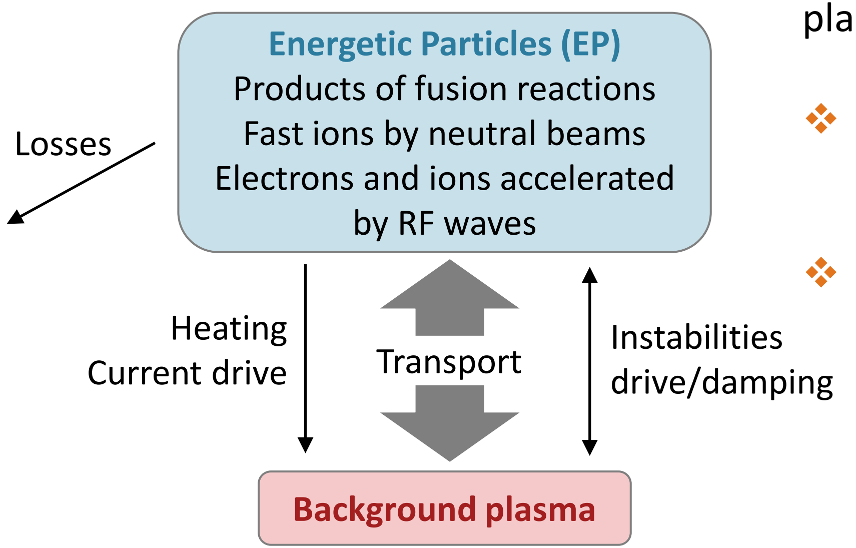
Energetic particle confinement is essential for high performance of the fusion plasma devices

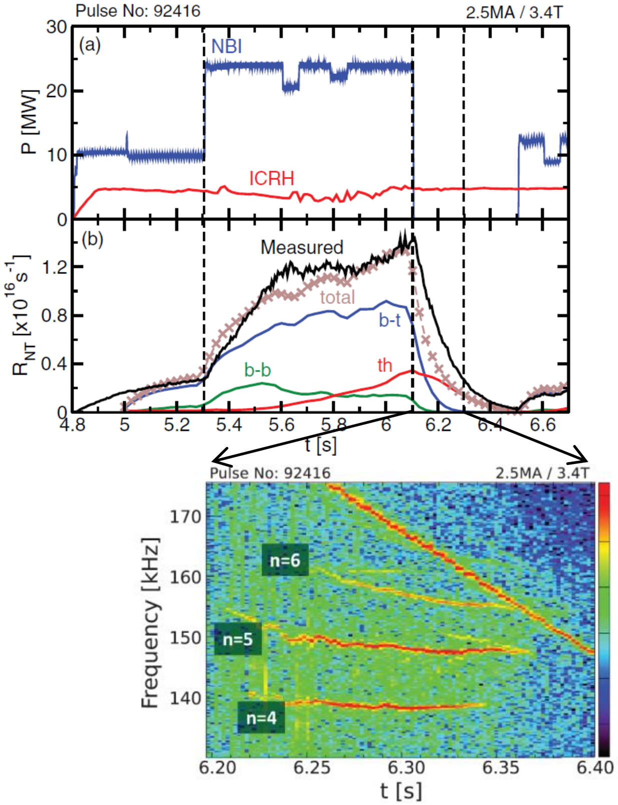


ITER performance will rely on sufficient confinement of plasma energy and particles.

- DT campaigns on the smaller machines help to expand our knowledge towards the ITER plasmas.
- One of the JET DTE2 campaign goals is to demonstrate clearly α-particle impact on the plasma performance:
  - plasma heating by α-particles and consequence for H-mode access and exit;
  - Alfvén Eigenmodes (AEs) destabilization and associated energetic particle transport.

*Fast ion transport (by J. Yang MF2-I26) and losses (by P. J. Bonofiglo MF2-I27).

Development and optimization of the after-glow scenario with DD plasmas is required further projections to DT plasmas



R. Dumont et al, Nucl. Fusion 58 2018

- Past DT campaigns, JET DTE1 and TFTR, proved that observation of α-driven TAEs was a challenging task.

- The after-glow scheme has been developed for a high-performance discharge to observe the α-driven AEs in the afterglow phase:
  - the NBI power is switched off abruptly;
  - the faster decay of the fast ions compared to the fusion α particles.

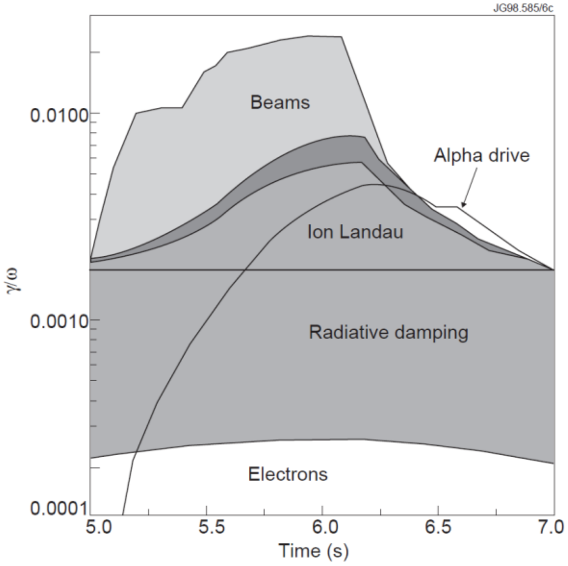
- As part of preparation for the DTE2 campaign, the after-glow scenario has been developed on JET for DD plasma discharges with RF heating.

⇒ Remove RF to observe clearly destabilizing contribution from α-particles.

Outline

- Research goals
- Interpretative analysis of the after-glow phase
- Alfvén Eigenmode stability properties
- Optimization of the NBI heating scenario
- Summary of results

Consequences of fast ion transport on the AE mode stability properties and scenario development



S. E. Sharapov et al, Nucl. Fusion 39 1999

The main difficulty: strong AE damping by beam ions

I. Investigation of Alfvén Eigenmode stability and possible damping by beam ions during the 'after-glow' phase in DD plasma discharges with NBI heating only.

II. Optimization of the JET NBI heating scheme:

- to ensure fast slowing down of stabilizing beam ions along with elevated q-profile;
- to explore possibility of keeping a small amount of beam power from sources that do not provide substantial AE damping instead of switching off all NBI completely since some diagnostics rely on NBI presence.

The TRANSP code is the main tool used for time-dependent interpretative and predictive plasma analysis

Input profiles

Full equilibrium and/or plasma boundary (RZ)

I_p, q

T_e, T_i, n_e

P_{rad}, impurity, Z_{eff}

Auxiliary heating (NBI, ICRH, ECRH, LHCD)

…

TRANSP[1,2]

Plasma transport equations

Energy balance

Particle balance

Momentum balance

NUBEAM[3]

Accounts for neoclassical EP physics

EP slowing down and atomic physics

Beam ion source and distribution

Predictive module PT-Solver[4]

Plasma equilibrium TEQ

Current density diffusion

Electron/ion energy and particle diffusion

+ TORIC, GENRAY/CQL3D (link to Wilkie's talk MF1-I43), the free boundary equilibrium solver, …

Output profiles

Plasma pressure

Beam ion distribution

Input data for MHD mode stability and/or gyrokinetic codes

…

Link to Francesca's talk MF1-I45

1 R.J. Hawryluk, in Physics of Plasm. Close to Thermonucl. Cond., ed. by B. Coppi, et al., (CEC, Brussels, 1980), Vol. 1, pp. 19-46.

2 Breslau, Joshua, Gorelenkova, Marina, Poli, Francesca, Sachdev, Jai, and Yuan, Xingqiu. *TRANSP*. Computer Software. USDOE Office of Science (SC), Fusion Energy Sciences (FES) (SC-24). 27 Jun. 2018. Web.

3 A. Pankin, D. McCune, R. Andre et al, Computer Physics Communications Vol. 159, No. 3 (2004) 157-184.

4 X. Yuan et al., 54th Annual Meeting of the APS Division of Plasma Physics (2012).

NOVA and ORBIT provide information on mode spectrum and resonance interaction between beam ions and modes

TRANSP

Beam ion distribution
Input data for MHD mode stability codes

NOVA

The linear ideal eigenmode solver to find the solutions of ideal MHD
Used for AE structure computations

C. Z. Cheng, M. C. Chance, Phys. Fluids 29, 3695 (1986)

ORBIT

Hamiltonian guiding center particle motion code
Analyses EP transport in terms of (E, P_ζ, μ)

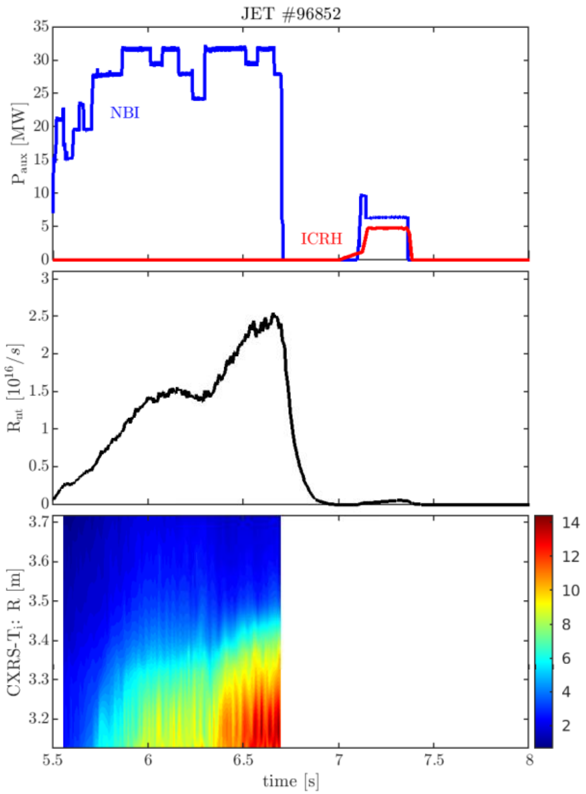
R. B. White & M. S. Chance, Phys. Fluids 27, 2455 (1984)

Stand-alone NUBEAM

Accounts for neoclassical EP physics
EP slowing down and atomic physics
Beam ion source and distribution

A. Pankin, D. McCune, R. Andre et al, Comp. Phys. Com. 3 2004

"Full" after-glow JET plasma discharges are of high level of complexity for numerical analysis

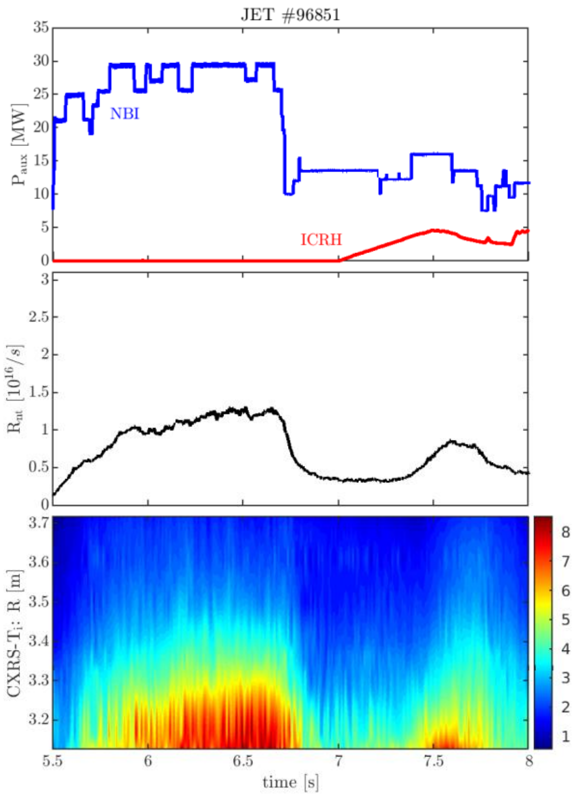


- Developed DD after-glow scenario:
  - high-performance, 30 MW NBI;
  - low density, high T_e and T_i, ITBs.
- Important diagnostic information depends on the presence of particular NBI injectors:
  - T_{imp} measurements, MSE constrained q-profiles.

⇒ We focus on analysis of the partial after-glow that has more detailed measurements during the after-glow phase.

There is an issue when a high-quality figure is generated by Matlab. Will be updated.

More detailed diagnostic information is available for the partial "after-glow" JET plasma discharges

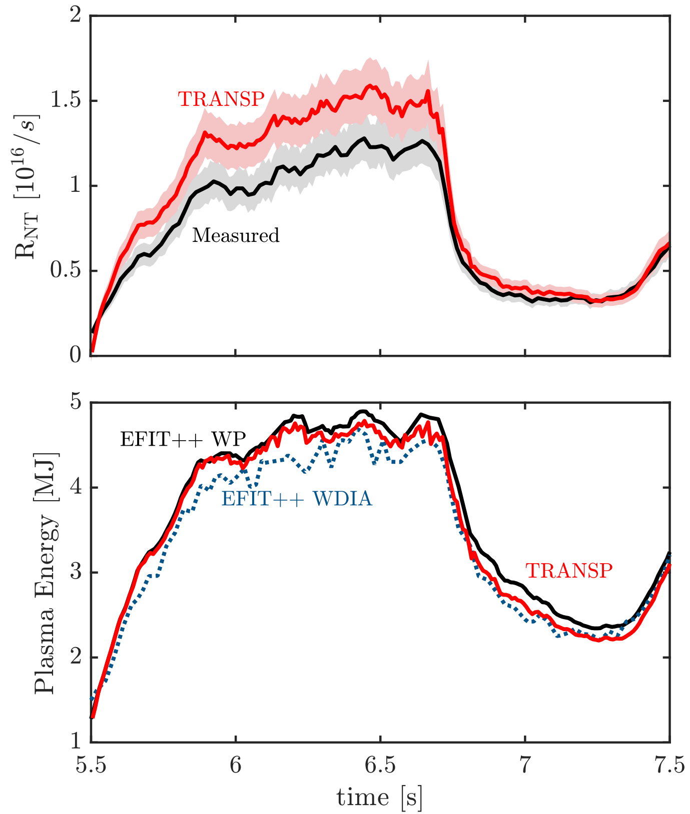


- For our purpose, **#96851** is a good candidate for analysis thanks to
  - a) long NBI phase, no RF;
  - b) MSE q-profile and Ti-CXRS measurements after the NBI major drop at 6.7 s since some beams remain operating.
- **Plasma parameters:**

- H-mode discharge with 96% D (major input gas) and 4% H (minority ions heated by ICRH).
- Impurities: Be, Ni (related to the RF antenna operation during previous discharges), W (ITER-like wall).
- D-NBI 15 beams (max 30 MW); ICRH ramp-up from 47 s.

There is an issue when a high-quality figure is generated by Matlab. Will be updated.

TRANSP interpretative analysis of the partial “after-glow” JET plasma discharge #96851

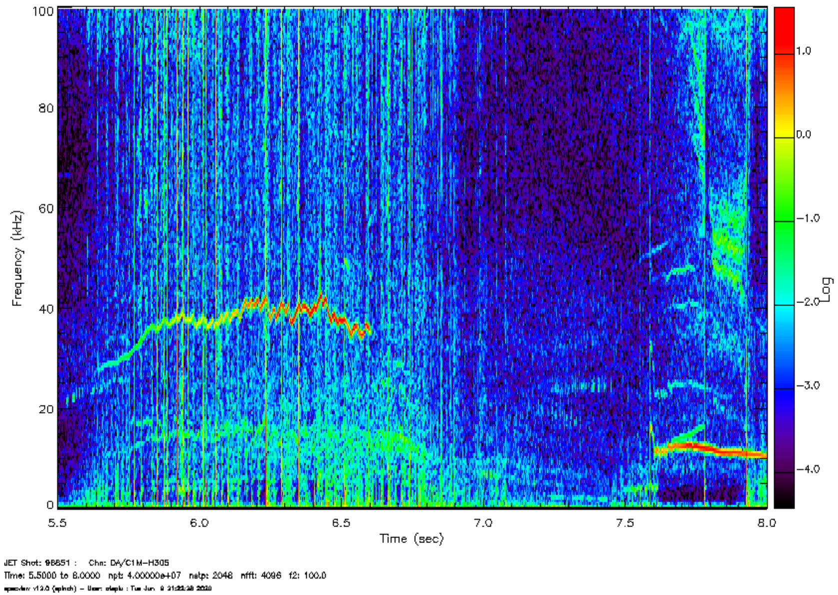


TRANSP settings:

- TRANSP time window [46.0- 47.5] s, NBI-only + ICRF ramp-up phase.
- Prescribed EFIT++ plasma equilibrium and q-profiles with MSE constraint.
- Fitted profiles of T_e, n_e, T_i and ω_{AF} on $(\sqrt{\psi_N}, t)$.
- Prescribed impurity (Be, Ni, W) and P_{rad} profiles prescribed on $(\sqrt{\psi_N}, t)$.

$\Rightarrow$ *Todo: uncertainties in the data and simulation results*

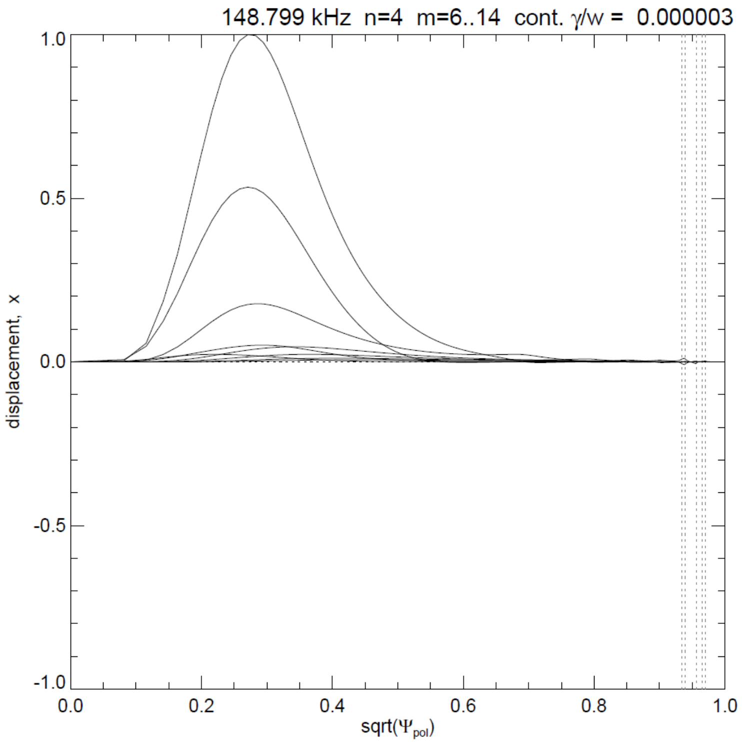
To improve analysis we assess uncertainties in the input profiles and their influence on the simulation results



- Consistent plasma equilibrium is obtained with multiple iterations in the TRNAPS+EFIT++ loop.
- Uncertainties in the input profiles like the impurity ion temperature (no data within rho~0.2) and electron density;
- the plasma composition (thermal ion transport models are not accurate);
- The MHD mode at 5.5-6.7 s, NTM n=4 (rho~0.4-0.5) might affect FI propagation to the core region. Hard to estimate quantitively effects.

**This slide is under development. Suggestions are welcome.*

Mode spectrum and stability properties
Damping rates



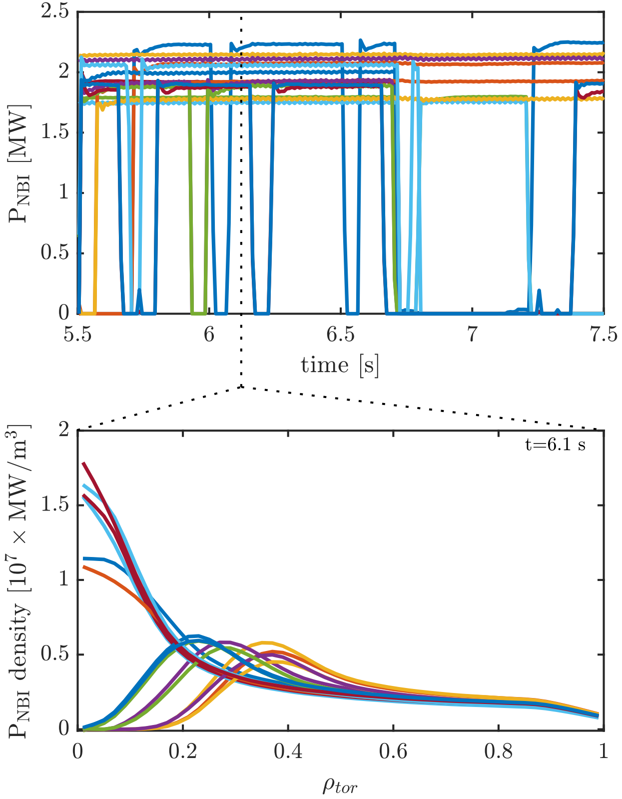
alpha-particle peaked near axis => need AE existing in the spectrum near the axis to destabilize them => vary FI distribution to vary beam ion damping near the axis. Maximized Off-/on-axis beam voltage varies FI within 0.2

* Here will need any info/damping rates coming from NOVA?

**This slide is under development. Suggestions are welcome.*

Slide on motivation for NBI optimization approach

NBI optimization within the developed scenario is limited mostly by the beam voltage variation



- Modification of the beam ion properties is the only way to vary and to build a specific FI distribution.
- With modified FI distribution one can vary mode stability properties but not the mode spectrum.

15 beams 30 MW in total: 6 on-axis and 9 off-axis beams.

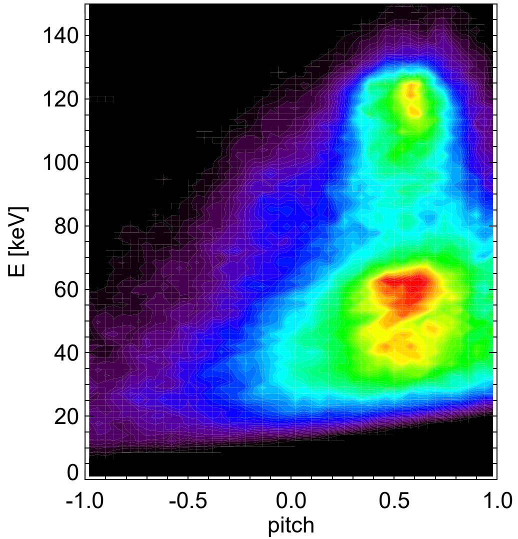
- Optimization of the JET NBI heating scheme:
  - a) maximize voltage of the off-axis beams;
  - b) maximize voltage of the on-axis beams.

* To keep the total power unchanged, the voltage of the remain beams have to be reduced:

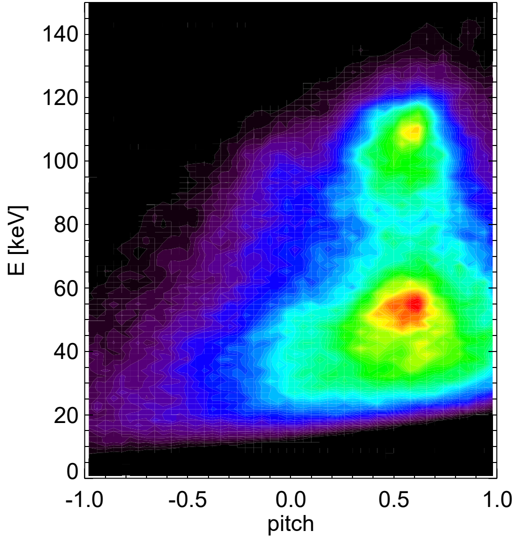
Av. per beam 111 keV → 125 keV → 14 keV reduction

Fast ion distribution is affected by the beam voltage
We are interested in the core region

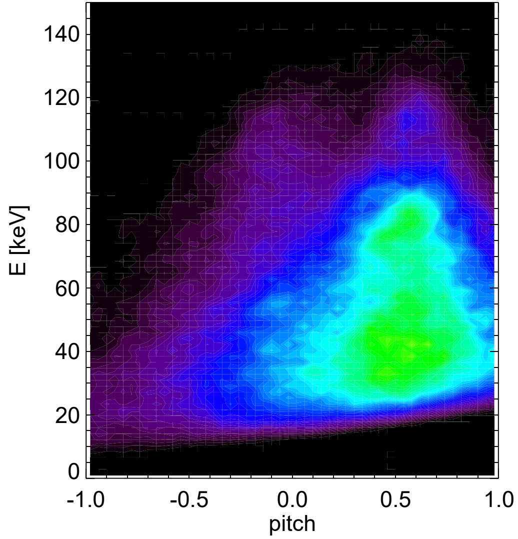
On-axis voltage maximized



Reference



Off-axis voltage maximized

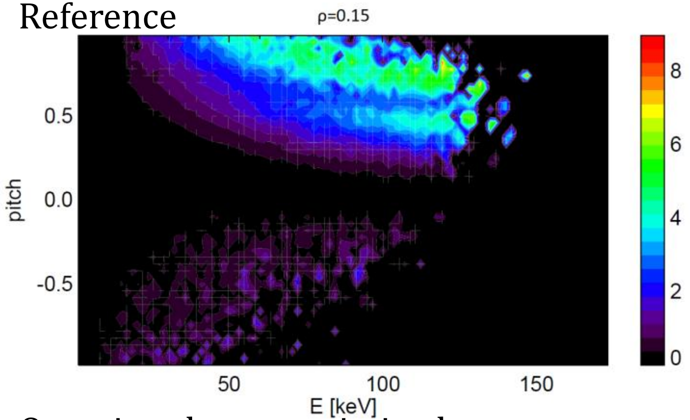


- Up to 5% increase in fast ion density at ρ=0.1.
- “Bump-on-tail” feature near the core is preserved.

- Up to 15% drop in central fast ion density at ρ=0.1.
- “Bump-on-tail” feature near the core is also reduced.

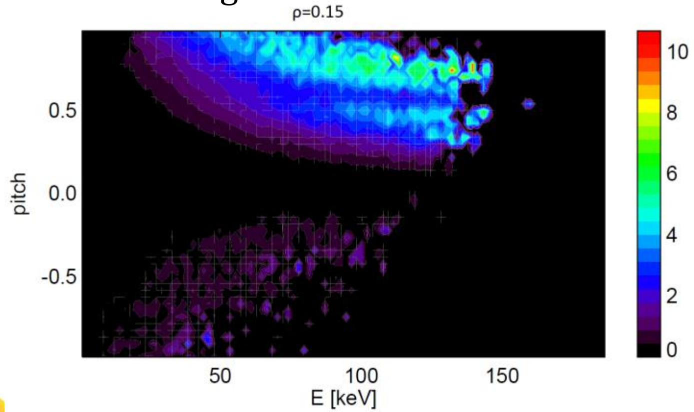
ORBIT provides information on the regions of resonance interaction between AEs and fast ions

Reference

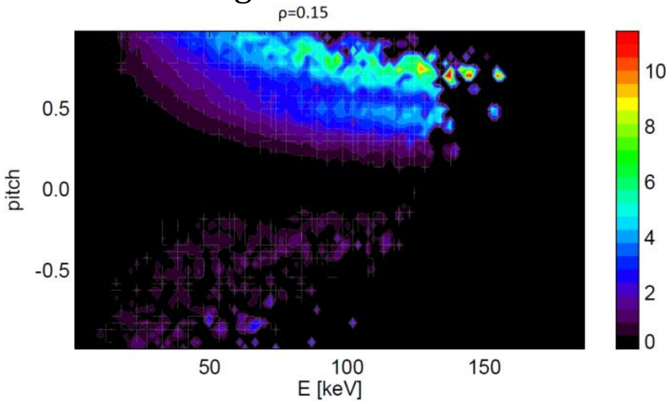


- Resonance interaction between AEs and co-passing fast ions.
- Next step: use stand-alone NUBEAM to estimate the mode growth rate.

On-axis voltage maximized

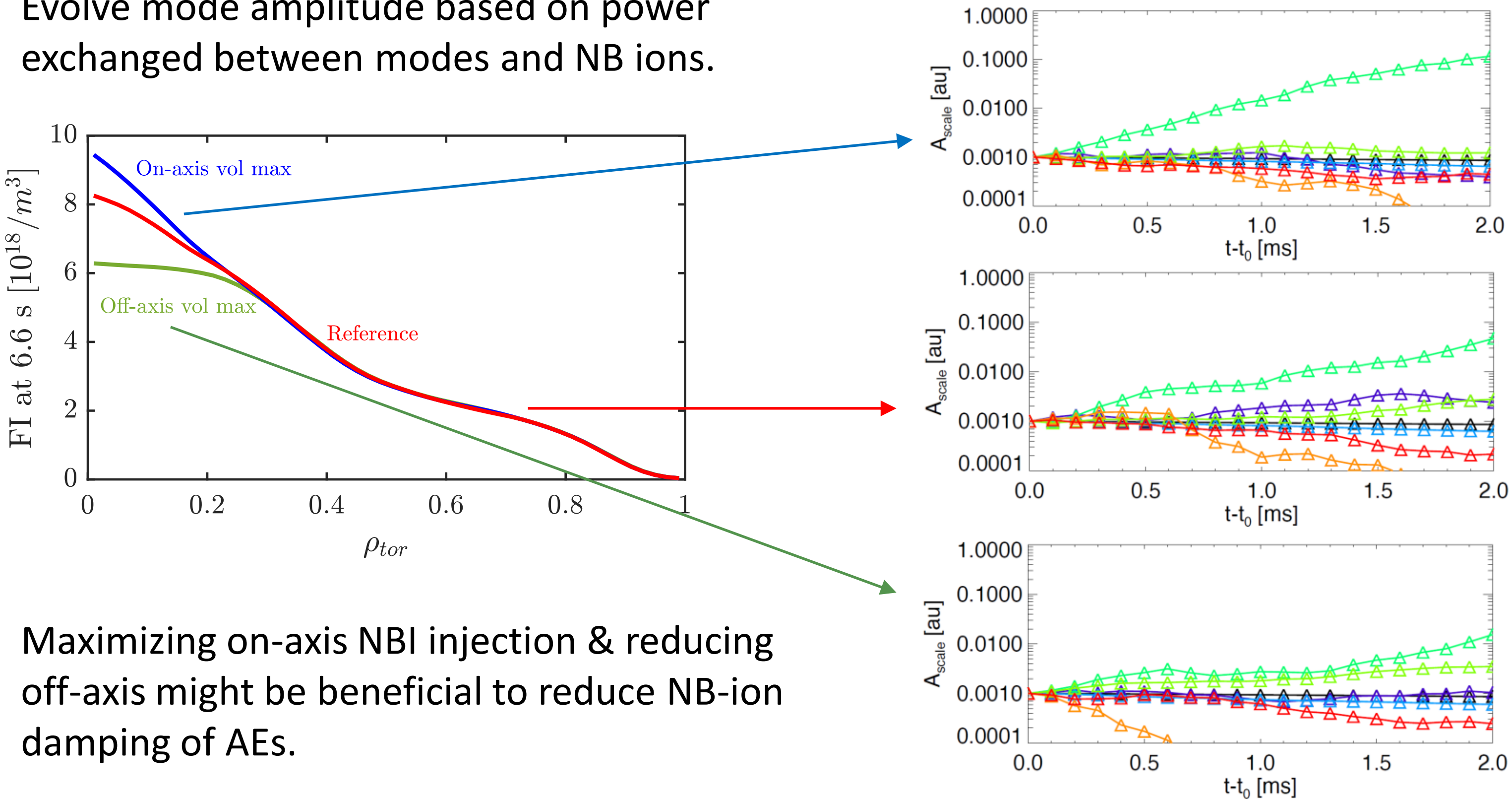


Off-axis voltage maximized



Drive is enhanced for some modes, mostly because of increased core NB ion density and gradients

- Evolve mode amplitude based on power exchanged between modes and NB ions.



- Maximizing on-axis NBI injection & reducing off-axis might be beneficial to reduce NB-ion damping of AEs.

Conclusion

- Projections from DD to DT plasmas will need to include AE mode stability analysis for developed and optimized NBI scenarios.

- TRANSP interpretative analysis is the starting point for numerical investigation of AEs destabilization in the planned JET DTE2 discharges and their stability linear analysis with the NOVA code.

- We have assessed uncertainties in plasma performance parameters depending on modeling assumptions and availability of diagnostic data, like plasma rotation profiles and measurements of ion temperature.

- Maximizing on-axis NBI injection & reducing off-axis might be beneficial to reduce NB-ion damping of AEs.

Motivation (1-2 slides)

Reliable projections from existing JET DD plasma discharges are required to develop a scenario allowing to observe alpha-particle driven modes in DT plasmas (check Joelle and Jeronimo slides from TFL meetings to clear the goals of the DT campaign). Jeronimo slide 6 in his goal's slides.
JET TFLs: "**Demonstrate clear α-particle effects:** compared to DTE1, JET has considerably improved diagnostic capabilities for energetic particles and thermal plasmas."

Motivation high level: why we are concerned by alpha-particles and their transport (EP confinement in fusion devices).

'After-glow': why did JET come up with the after-glow scenario? Refer to previous DT campaigns on TFTR and JET DTE1. Mention that we want to avoid RF and RF-driven AEs.

R. Dumont paper: no clear conclusions on alpha-driven TAEs can be taken from DTE1 and TFTR.

Discuss how heating scenario can affect EP distribution (AEs are sensitive to heating scenario) => how can we modify EP distribution.

Favorable conditions to observe Alfvén Eigenmodes driven by alpha-particles include reducing mode damping by beam ions and maintaining minimum q at high values to destabilize modes.

Research goals (1-2 slides)

a) Investigation of Alfvén Eigenmodes (AE) stability and possible damping by beam ions during the ‘after-glow’ phase.

b) Optimization of the JET NBI heating scheme:

- to ensure fast slowing down of stabilizing beam ions along with elevated q-profile;
- to explore possibility of keeping a small amount of beam power from sources that do not provide substantial AE damping instead of switching off all NBI completely since some diagnostics rely on NBI presence.

c) Title: “Features of energetic particle transport …”: discuss EP transport in terms of the EP distribution function and its modification by NBI heating scenario.

d) Discuss main damping mechanisms (ion Landau damping).

TRANS/NUBEAM are advanced tools for modelling time-dependent plasma discharges. Highlight that we have to simulate properly time-dependent cases.

Interpretative analysis of the after-glow phase (7-8 slides)

Reliable interpretative analysis of the after-glow phase is essential for mode stability analysis and NBI optimization:

3. Discuss experiments with full and partial ‘after-glow’ phases and explain difficulties for analysis: limited or luck of diagnostic data (1-2 slide).
4. TRANSP analysis of the JET discharge #96851 demonstrating partial after-glow (3 slides):
   - profiles mapping, TRANSP-EFIT++ consistent equilibrium data;
   - discuss EP transport after the NBI power drop: the beam ion slowing down time, characteristic rates (can we compute any mode damping rates from TRANSP output profiles?)
5. TRANSP analysis of the JET discharge #96852 with the full after-glow phase (2 slides):
   - discuss profiles (T_i, rotation, impurities) unavailable after the NBI full stop and propose scaling based on #96851 data (in terms of decay rates);
   - discuss differences between #96851 and #96852 (i.e. partial and full after-glow) in terms of EP transport: EP distribution and the beam ion slowing down time.
6. Summarize the analysis and note that the following discussion on mode stability analysis is focused on #96851 since more reliable analysis is available (1 slide).

Mode stability analysis (2 slides)

by NOVA/NOVA-K (**ToDo**):

- Information on the AEs spectrum for the reference run (location of the modes).
- Mode damping rates?

by ORBIT (**ToDo**): described in the phase space negate/positive kicks per beam to analyse ability of generated fast ions to destabilize/stabilize the AEs.

Damping mechanisms: ion Landau damping

DT: sharp gradient in alpha-particle distribution, they are mainly near the axis. Most potential AEs are driven by alpha-particles. It is important to have a scenario with AEs located near the axis.

NOVA: two sets of modes, near the axis and at the mid-radius. We need to destabilize those located near the axis.

Consider destabilizing contribution from alpha-particles, removing RF (i.e. remove additional destabilizing source).

Optimization of the JET NBI heating schemes (5-6 slides)

Mention why we focus on the NBI heating scenario. Developed DD scenario will be unchanged for DT operation. Modified beam settings is the only way to modify FI distribution and help to build a specific FI distribution.

With modified FI distribution only mode stability properties are modified, so we need only ORBIT to judge on modification in the mode stability properties.

If q-profiles is modified than we need to rerun NOVA to judge on the modification in the mode spectrum and location of the modes (if they become closer to axis for example).

Optimization of the JET NBI heating scheme (3 schemes discussed, 3 slides):

a) Vary/maximize voltage of the off-axis beams (predicted q, small effect on q, large in beam ion distribution.

b) Put more beam power to off axis beams (larger effect on q) keeping total NBI power unchanged (to keep an additional off-axis beam on one has to switch off one of the on-axis beams) q and T_e/T_i predicted profiles.

c) Reduce total NBI power during the after-glow phase with q and T_e/T_i predicted profiles (not tested yet, **ToDo**).

d) These predictive runs are also subject of the mode stability analysis (2-3 slides):

- discuss differences in terms of EP transport: how beam ion slowing down times and distribution are modified (**requires** NUBEAM fast ion data and ORBIT runs);
- discuss mode stability properties (**requires** NOVA runs).